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Research and Development Report

Prediction of SWATH Cross-Structure Slamming Pressures

by

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ABSTRACT

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ADMINISTRATIVE INFORMATION

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INTRODUCTION

The slamming loads acting on the cross-structure of a SWATH ship can present a serious problem for operations in a heavy seaway. It is therefore, important for the designer to have available the means for assessing the slamming characteristics of a SWATH ship early in the design stage. The methods employed for monohulls do not appear to apply directly to the SWATH ship (at least without some modifications), and an investigation was made to determine procedures for estimating slamming loads more appropriate for the SWATH.

The method developed for monohulls by Ochi[1] assumes that a slam occurs when the point of impact contacts the water with a velocity that exceeds a certain critical value. An analytical expression can be derived defining this event by assuming that the relative motion between the point of contact and the free surface is a stationary random Gaussian process. The critical or threshold velocity for a 520 foot (158 meters) Mariner as defined by Ochi from model experiments is 12 ft/sec (3.7 m/sec). This value is Froude scaled to obtain the equivalent values for ships of different lengths. Ochi also provides analytical expressions for estimating extreme values of impact pressure based upon the assumption that the relative velocity is a stationary random Gaussian process and that the impact pressure is proportional to velocity squared.

The applicability of these relationships, developed for the keel slamming of a monohull, to the cross-structure slamming of a SWATH ship has not been verified. Experimental data from three dimensional drop test of wedges by Chuang[2] and subsequently applied to a catamaran cross-structure suggest that the slam pressure of a SWATH cross-structure is dependent upon both the relative velocity and the impact angle at the point of impact. Experiments were necessary to establish whether a relationship existed between slam pressure and the relative velocity and angle of impact between the cross-structure and free surface upon impact for the SWATH ship. Fortunately, a comprehensive model test program had been initiated for support of the T-AGOS design which included impact pressure measurements on the cross-structure. Additional instrumentation was added at one gage location to measure cross-structure relative velocity and angle of impact with respect to the free surface.

DESCRIPTION OF EXPERIMENT AND INSTRUMENTATION

As previously indicated, data for these studies were obtained during a much broader model experiment program for the T-AGOS SWATH design. A 1/22 scale model was instrumented to obtain a comprehensive seakeeping evaluation including slam pressures on the cross-structure. All that was needed for these studies was the addition of suitable instrumentation for measuring velocity and angle relative to the free surface at the point of impact.

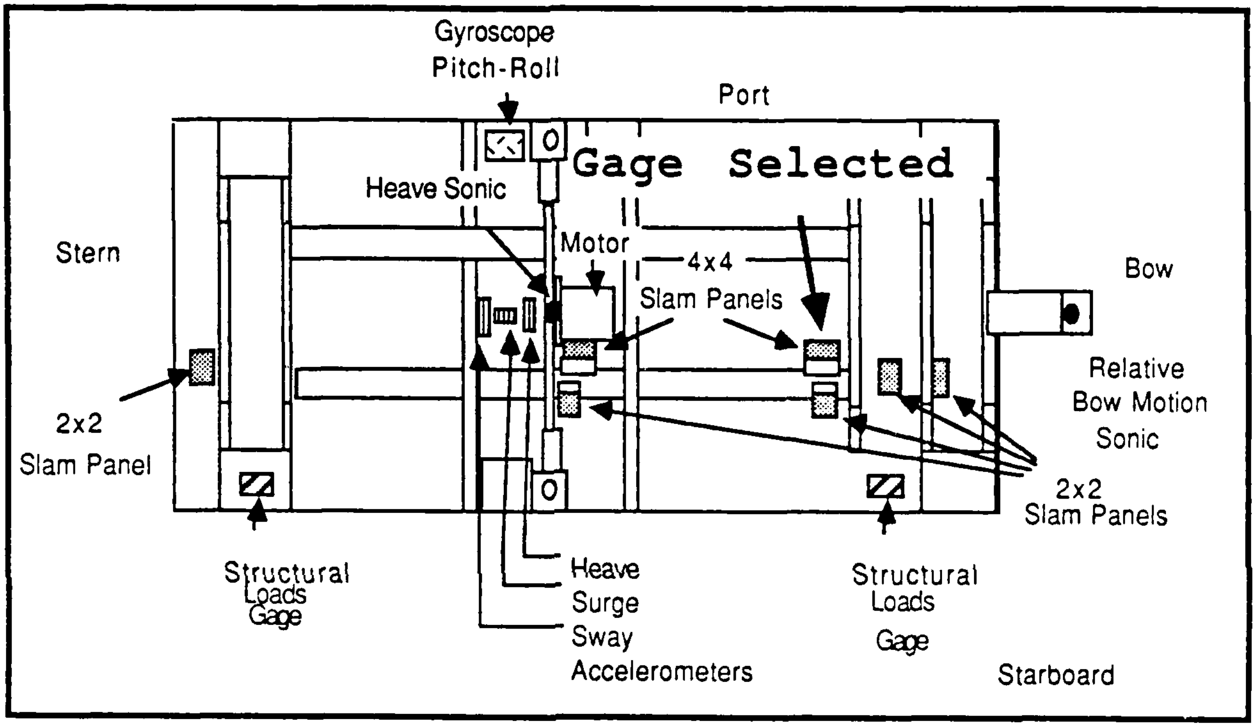

Figure 1 - Location of Pressure Gage

The pressure gage consisted of a strain-gaged panel which was calibrated to measure the average pressure over an area corresponding to 4 ft. by 4 ft. (full scale). The location of this panel on the cross-structure is shown in Figure 1. Three wire probes for measuring relative motion between the free surface and the structure were mounted in a triangular pattern encompassing the pressure gage. Figure 2 is a sketch showing the probe spacing around the pressure panel. The relative motion data were filtered to prevent aliasing and recorded on digital tape at a rate of 6 samples per second. This is the normal procedure for recording relatively low frequency seakeeping data. Because of the rapid rise times associated with a slam, which would require an extremely high sample rate to resolve, the pressure data were recorded on analog tape along with other structural load data. A relative motion measurement was included on the analog tape to time correlate slam pressure with the relative velocity and angle on the digital tape.

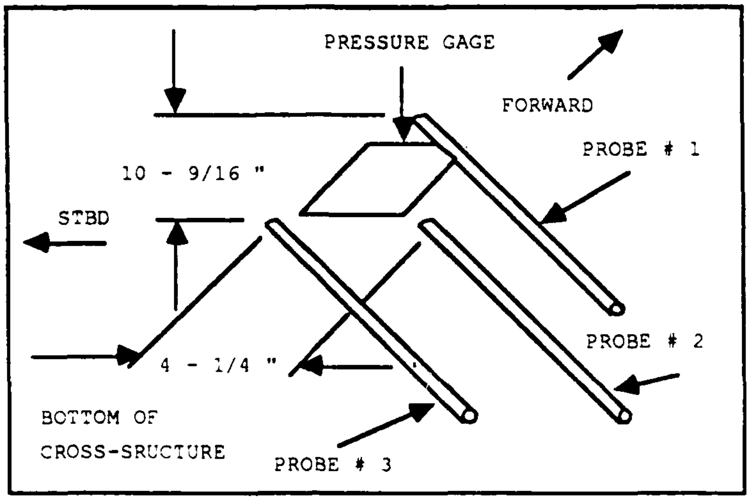

Figure 2 - Sketch of Relative Motion Probes

The primary experimental program investigated the seakeeping performance of the T-AGOS in various sea conditions at several speeds and headings; however, only two runs were selected for this investigation based upon sample size of the number of impacts. Operation in head seas at 8 knots in a sea state 9 and at zero speed in a sea state corresponding to hurricane Camille produced a significant number of impacts on the cross-structure which made these data amenable to a comprehensive statistical analysis. A much lesser number of impacts occurred at other conditions which may be relevant to the T-AGOS seakeeping assessment, but were not considered to have sufficient sample size to warrant detailed statistical examination.

METHOD OF ANALYSIS

Figure 3 is a graphic representation of the digital data recorded by the relative wave height probe as a function of time.

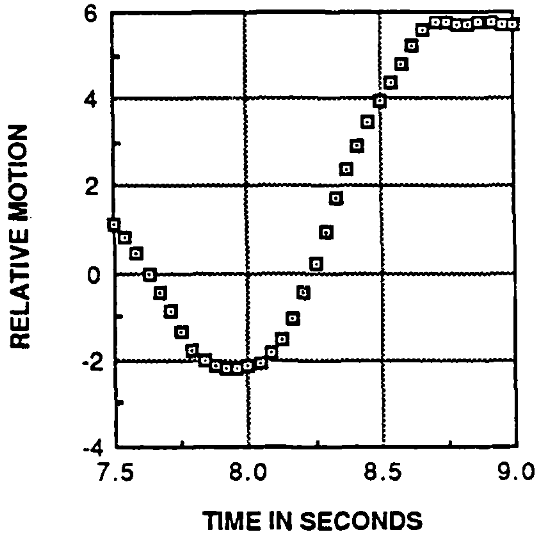

Figure 3 - Relative Motion Time History

The data show the saturation of the probe when deck wetness occurs which is typical during a slam event. The synthesized time history of the relative wave height from the digital data was readily correlated with the corresponding channel on the analog tape containing the impact pressure data. Thus each cross-structure impact recorded on the analog tape could be closely associated with the corresponding digital time histories of the relative wave height probes.

Relative velocity was computed by numerically differentiating the relative wave height displacement. Three points were used in a polynomial fit to find the value of the derivative at the end point which is given by

$$df(t_2) = \frac{1}{2h}\left[f(t_0) - 4f(t_1) + 3f(t_2)\right]$$

where, h = time interval between data points.

The values of the computed velocity from the three relative wave height probes were averaged to obtain the velocity at the center of the pressure gage. The impact was assumed to occur at the instance prior to deck wetness as indicated by the flattening out of the relative wave height time history. (See Figure 3.)

The angle of impact was calculated from the relative wave height measurements assuming the free surface to be a simple plane surface between the three probes. A plane can be represented by the equation

$$Ax + By + Cz + D = 0 \quad \text{or in vector notation} \quad \mathbf{A}\cdot\mathbf{r} + D = 0$$

where the vector **A** is directed along the normal to the plane with **r** being the position vector. If the z axis is located parallel to the wave wires and perpendicular to the cross structure at the gage location then the directional cosine of the normal relative to the z axis also defines the angle of the free surface with respect to the cross-structure. In this case the z coordinate represents the free surface relative to the cross-structure. The appropriate directional cosine is given by

$$\cos \alpha_z = \frac{-C\ \mathrm{sign}(D)}{\sqrt{A^2 + B^2 + C^2}}$$

where,

$$A = \begin{vmatrix} y_1 & z_1 & 1 \\ y_2 & z_2 & 1 \\ y_3 & z_3 & 1 \end{vmatrix} \quad ; \quad B = \begin{vmatrix} z_1 & x_1 & 1 \\ z_2 & x_2 & 1 \\ z_3 & x_3 & 1 \end{vmatrix} \quad ; \quad C = \begin{vmatrix} x_1 & y_1 & 1 \\ x_2 & y_2 & 1 \\ x_3 & y_3 & 1 \end{vmatrix}$$

and

$$D = -\begin{vmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ x_3 & y_3 & z_3 \end{vmatrix}$$

The subscripted z values correspond to the three relative wave height measurements at the instant of time that the impact angle is calculated and the x,y values locate the corresponding probes on the cross-structure. As in the case of the relative velocity, the impact angle was computed at the instance just prior to the wetting of the cross-structure.

PRESENTATION OF RESULTS

Plots of the impact pressure variation with relative velocity are presented in Figures 4 and 5 respectively for zero speed and 8 knots (equivalent full scale) in head seas.

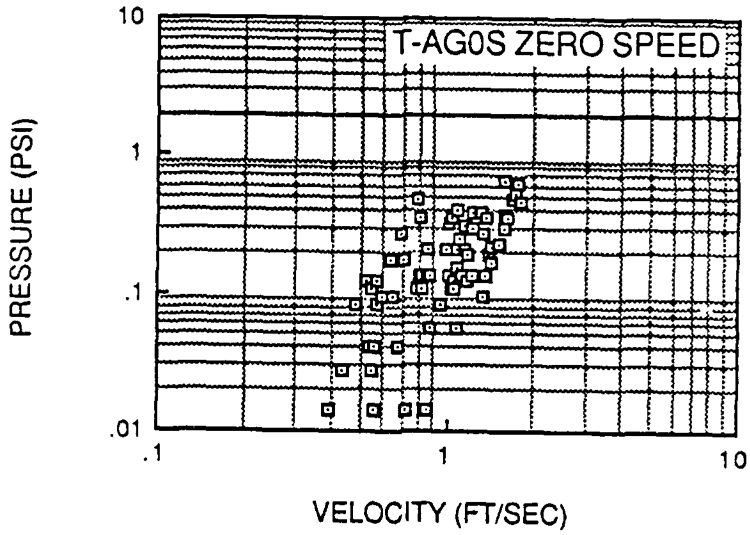

Figure 4 - Impact Pressure Variation with Velocity - Zero Ship Speed

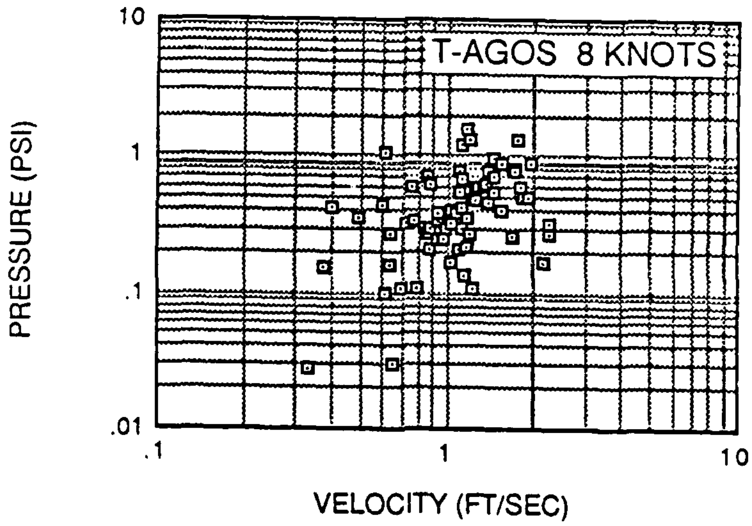

Figure 5 - Impact Pressure Variation with Relative Velocity - 8 Knots Ship Speed

It is quite evident from these plots that there is a considerable amount of scatter in these data suggesting the possibility that other factors besides relative velocity influence the magnitude of the slam pressures. The results of Chuang[2] indicate a strong correlation of impact pressure with the relative angle of the free surface and structure at the point of impact. Accordingly, the pressure was normalized by the velocity squared using the relationship

$$p = \frac{\rho}{2} k V^2$$

where p is the pressure in psi, and the k values were plotted with respect to the impact angle.

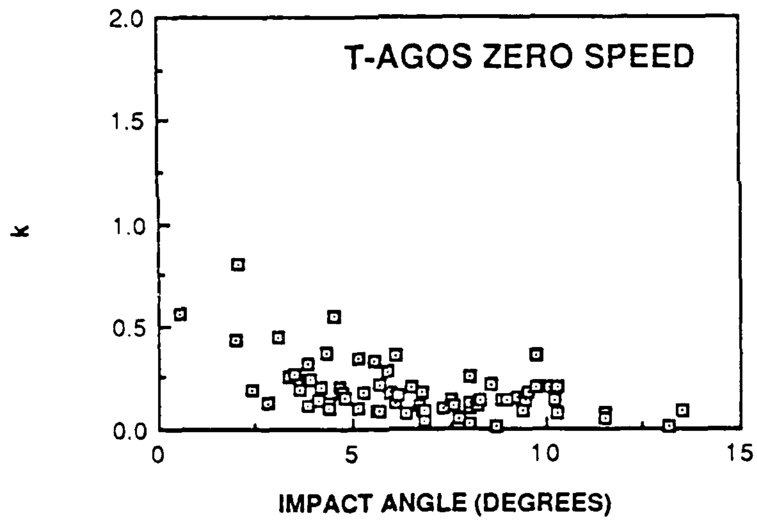

Figure 6 - Impact Pressure Variation with Impact Angle - Zero Ship Speed

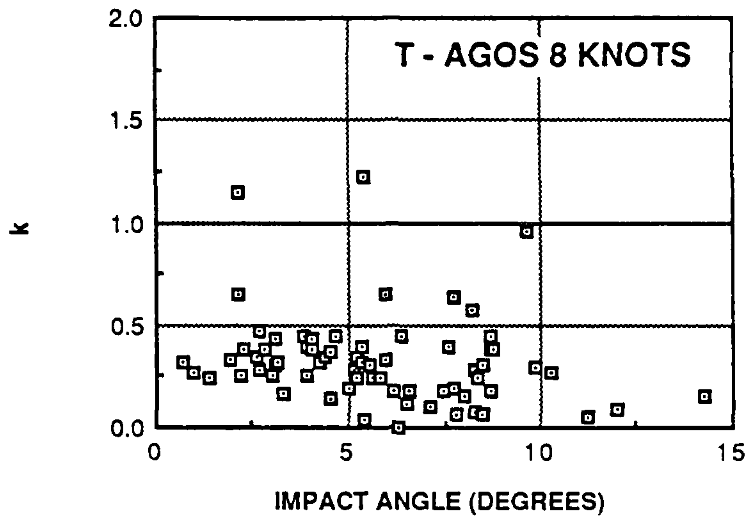

Figure 7 - Impact Pressure Variation with Impact Angle - 8 Knots Ship Speed

The pressure data do not show any consistent trend with variation in impact angle; although, the zero speed data presented in Figure 6, show slightly less scatter than the results obtained for 8 knots shown in Figure 7. A contributing factor causing the scatter may be the inability to determine the velocity with sufficient accuracy at the instance of impact. Numerical differentiation is inherently difficult because of its tendency to magnify small discrepancies. Also, at the time of impact the relative motion signal becomes saturated and no longer indicative of the relative motion. Consequently, the relative impact angle, as well as the relative velocity, are taken as the values that occur just slightly before impact. Another possible source of discrepancy may due to the large panel area over which the pressure is measured and its dynamic characteristics. In addition to these errors there appears to be other factors, not presently accounted for, that influence the magnitude of the impact pressure experienced by the ship.

Since there does not appear to be a clear relationship between the impact pressure and the relative velocity and angle of impact it was necessary to examine a slightly more general approach. Dinsenbacher[3] has demonstrated that the impact pressures can be describe statistically by an exponential probability distribution function where the probability P of the pressure p being less than some value "a" is given by

$$P(p \leq a) = \int_0^a \frac{C}{\sqrt{E}} e^{-\frac{C}{\sqrt{E}}p}\, dp \qquad [1]$$

where, E = mean square pressure.

and, C = constant = $\sqrt{2}$.

Figure 8 shows that equation [1] is fairly representative of the two sets of data presently being examined.

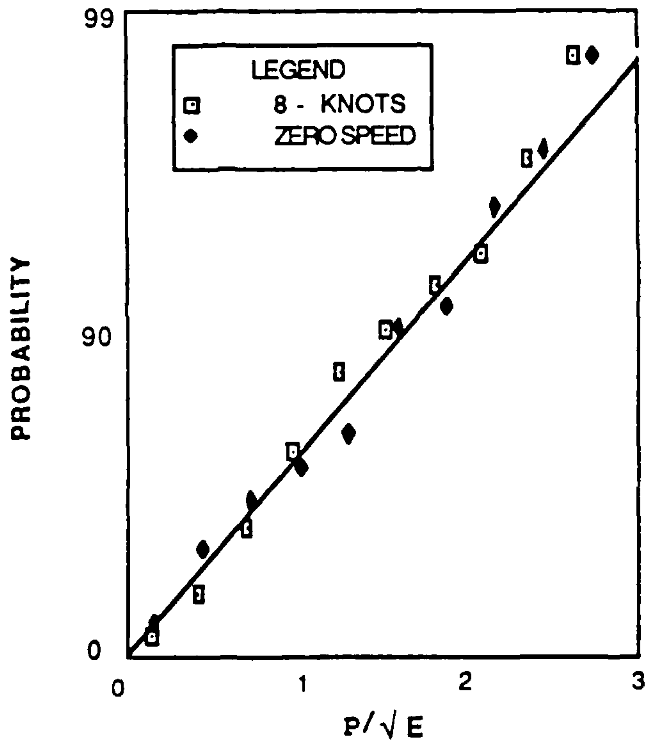

Figure 8 - Impact Pressure Probability

Ochi and Motter[4] had previously obtained similar results for bottom slamming by assuming that the relative velocity is a narrow band Gaussian process and the impact pressure is proportional to relative velocity squared

$$p = 2k_1 V^2$$

where, k_1 is a constant.

The narrow band Gaussian process defines the probability distribution of the velocities at impact as a Rayleigh distribution, and in this case the statistical properties of the impact pressures can be related to those of the relative velocity, i.e

$$f(p) = \frac{1}{4k_1\sigma_v^2} e^{-\frac{1}{4k_1\sigma_v^2}(p - p_*)} \qquad [2]$$

where, p = impact pressure = $2k_1 \cdot V^2$

p_* = threshold pressure = $2k_1 \cdot V_*^2$

σ_v = standard deviation of relative velocity

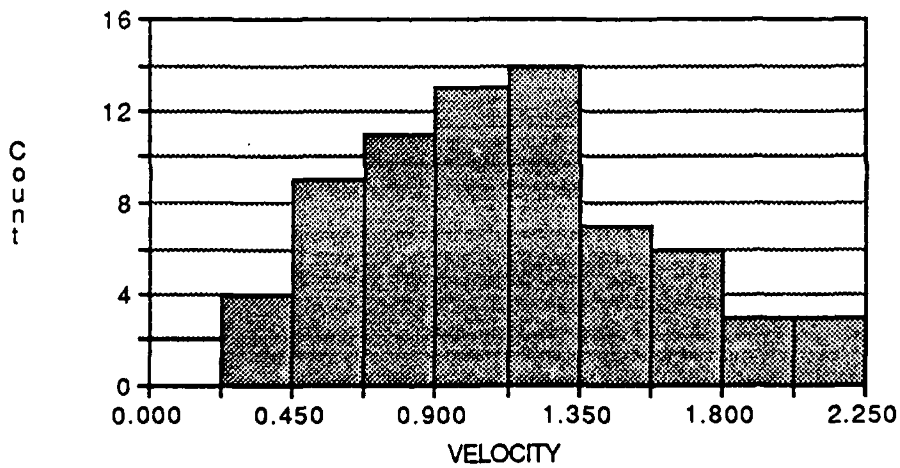

Figure 9 - Frequency Distribution of Relative Velocity - Zero Ship Speed

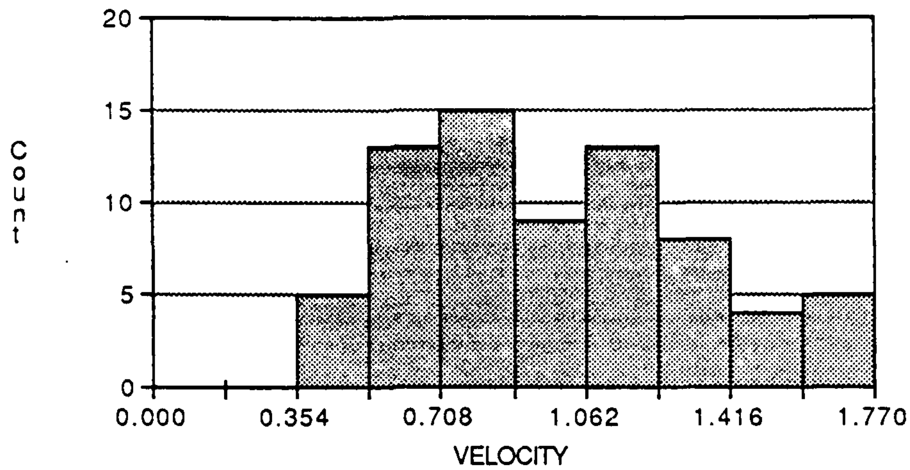

Figure 10 - Frequency Distribution of Relative Velocity -
8 Knots Ship Speed

The pressure data shown previously in Figures 3 and 4 indicates that the velocity squared relationship does not fit the data without considerable scatter. Also, the frequency distributions of the relative velocity at impact, shown in Figures 9 and 10 for the results obtained at zero speed in sea state 8 and at 8 knots in sea state 9 respectively, do not appear to closely match a Rayleigh distribution as would be expected for a Gaussian process. Some of this discrepancy, as indicated previously, may be attributed to the inherent difficulty in measuring the velocity.

In spite of the above lack of strong correlation between velocity and pressure an attempt has been made to establish a statistical relationship between impact pressure and the relative velocity. If it is assumed that the root mean squared pressure is proportional to the mean squared relative velocity

$$\sqrt{\overline{p^2}} = C_o \overline{V^2} = C_o \sigma_v^2 = \sqrt{E} \qquad [3]$$

where,

$\overline{p}^2$ = mean squared pressure

C_o = arbitrary constant

σ_v= standard deviation of relative velocity

$\overline{V^2}$ = mean squared relative velocity then, Dinsenbacher's formulation [1] and Ochi's formulation [2] are interchangeable when the threshold pressure or velocity is zero. Reference (5) has demonstrated that the relative motions, hence σ_v, can in most cases be accurately estimated using the SWATH Seakeeping Assessment Program (SSEP) avoiding the need for experimentally determining rms pressure.

In order to partially verify this approach, calculations were made of some of the basic relationships predicted as a consequence of the above assumptions and compared with those obtained experimentally. These results are presented in Table 1. First, the average number of level crossings (N) were calculated for the zero level and the cross-structure level at the gage location using the formulation for a stationary Gaussian process

$$N = \frac{1}{2\pi} \frac{\sigma_v}{\sigma_r} e^{-\left(\frac{H^2}{\sigma_r^2}\right)} \qquad [4]$$

where, H = displacement at level crossing
σ_r = standard deviation of displacement
σ_v = standard deviation of velocity.

These results were compared with the actual number observed which is shown in Table 1.

Table 1 shows that the calculated estimates are in very good agreement with the observed results. It was also observed that the number of impacts was very close to the number of level crossings and that a threshold velocity analogous to that found for monohull bottom slamming does not appear to be a significant factor in the cross-structure slamming of the SWATH ship. Table 1 also presents the constant C_0 computed by taking the ratio of the root mean square pressure to the standard deviation of the relative velocity derived from its spectrum.

TABLE 1 - Level Crossings and Other Impact Parameters

	ZERO SPEED - SEA STATE 8		8 KNOTS - SEA STATE 9	
	COMPUTED FROM SPECTRUM	MEASURED	COMPUTED FROM SPECTRUM	MEASURED
NO. OF ZERO CROSSINGS*	0.46	0.48	0.54	0.52
NO. OF LEVEL CROSSINGS	0.13	0.12	0.21	0.27
RATIO OF RMS PRESSURE TO MEAN SQUARED RELATIVE VELOCITY TIMES DENSITY		16		26

* Crossings per second with positive slope (model scale)

It may be noted that the value of this coefficient obtained at 8 knots in sea state 9 is slightly higher than the value for zero speed in sea state 8. The two data spots are insufficient to determine if the difference reflects a genuine trend or simply experimental variations.

If equations [3] and [4] are assumed to apply to the SWATH cross-structure slamming then according to Ochi's formulation the extreme value of impact pressure is given by

$$\hat{p}_n(\alpha) = -\frac{C_o\,\sigma_o^2}{\sqrt{2}} \ln\left\{1 - (1-\alpha)^{1/n}\right\} \qquad [5]$$

where, $\hat{p}_n(\alpha)$ is the extreme value of the impact pressure whose probability of being exceeded in n impacts is equal to α. Equation [5] is only applicable to operating conditions in which the probability distribution and associated rms impact pressure are the same, i.e. same sea state, heading angle and speed. An equivalent expression can be found for assessing the probability of the extreme value in a combination of discrete sea, heading and speed conditions provided each of the probability distributions are known. Assuming that the probability density of the pressure in each condition is exponential, the probability α of exceeding an extreme value p is given by

$$\alpha = 1 - \Pi_i \left(1 - e^{-\frac{\sqrt{2}}{\sqrt{E_i}} \hat{p}} \right)^{n_i} \qquad [6]$$

where n_i = number of slams associated with i^{th} condition
and, $\sqrt{E_i}$ = rms impact pressure associated with i^{th} condition.

Equation [6] can be solved numerically to determine an extreme pressure associated with a particular probability or conversely the probability associated with an assumed extreme pressure.

SUMMARY AND CONCLUSIONS

Measurements of SWATH cross-structure impact pressures and the relative motions between the free surface and the structure at the point of impact on a 1/22 scale model of the T-AGOS were analyzed to determine the fundamental relationship between these parameters which could lead to a procedure for estimating the pressure from ship motion computations. The impact pressure was anticipated to vary as the square of the relative velocity, but the data showed considerable scatter when plotted in this fashion. Taking into account the angle of the free surface at the point of impact did not improve the correlation as was anticipated. The above disparity can in part be attributed to the inability to accurately determine relative velocity which required numerical differentiation of the displacement and possibly due to the large panel area over which the pressure was averaged.

Computation of the number of level crossings at the point of impact from measurements of the power spectrum agreed closely to the actual number observed. There was little difference between the number of level crossings and the number of impacts; therefore, the number of slams can be assumed equal to the number of level crossings with little error. This would suggest that the number of level crossings at the point of impact can be used directly as a crude assessment of the slam characteristics of the SWATH ship.

A more definitive assessment of SWATH slam characteristics can be made from ship motion computations by assuming that the rms impact pressure is proportional to the mean square relative velocity. Dinsenbacher has demonstrated from experimental data that the probability distribution of the impact pressure is exponential and completely defined by the rms pressure. The mean squared relative velocity, which can be computed with reasonable accuracy with the SWATH Ship Evaluation Program, can be converted to rms pressure assuming that proportionality is the same (or nearly so) for all SWATH ships. This latter assumption requires additional experimental verification.

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